PDV Systems and Cost Reductions

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Agenda

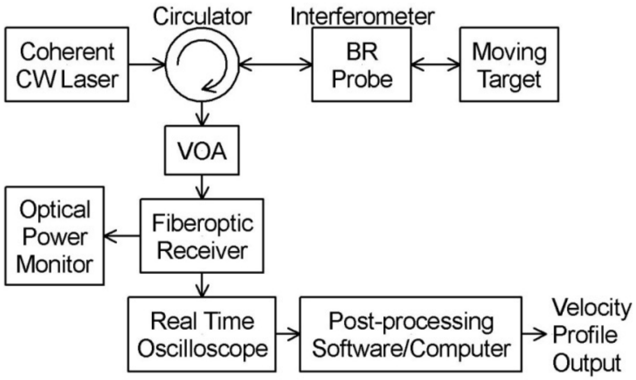
- Classical Photonic Doppler Velocimeter (PDV) Systems
- Example PDV equipment costs
- Spotting Laser
- Lasers, Coherence, and Optically Amplified Lasers
- Interferometry approximation for PDV
- Special Amplifiers and Frequency Dividers
- Counters with DAC and/or RAM
- Single Box PDV systems
- Food for Thought
- Conclusion

PDV Systems Review

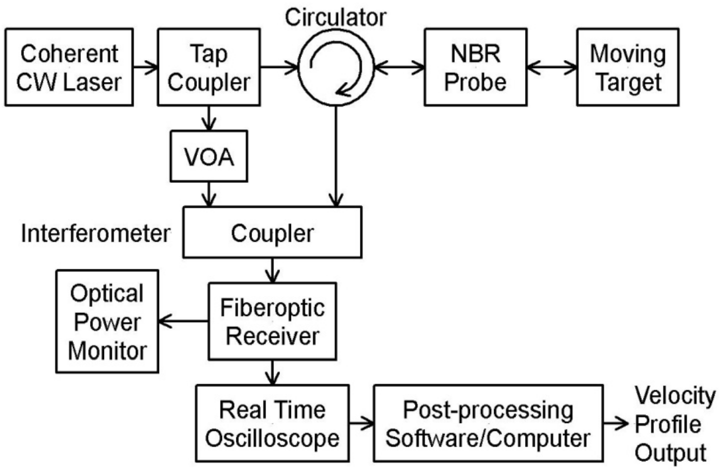
- Technology developed for over a decade, based on century old science
  - Well established, very successful, a material science renaissance!
  - Non-contact measurement of position, velocity, acceleration, and jerk possible
  - Based on optical interferometry, inherently position based, sub-micron resolution
  - "It's all over" in typically 100 ns, <u>100 us</u>, or 100 ms, depending on experiment
- Systems produced within PDV community
  - Typically use off-the-shelf components for availability (rarely used in telecom industry)
  - Commercial equipment emerging using industrial telecom components
- Basic classical PDV system consists of:
  - Continuous wave (CW) coherent laser source
  - Fiber optic components (circulator, couplers, attenuator)
    - Depends on probe type
    - Multi-way splitter of laser source often used in multi-channel systems
  - Probe, either Back-Reflecting (BR) or Non-Back-Reflecting (NBR) type
  - Moving target (the experiment!)
  - Fiber optic receiver (PIN or APD, AC or DC coupled) and input power monitor
  - Real-time oscilloscope
  - Oscilloscope trigger input (usually from experimental setup)
  - Post-processing software and computer (outputs velocity profile of target)

Classical Single-Channel PDV Systems and Performance

Back-Reflecting (BR) Probe type



Non-Back-Reflecting (NBR) Probe type



Typical system <u>losses</u> (1550 nm, VOA=0)
Laser to probe tip (glass side) = 1 dB (20.6%)
Probe BR of laser to ORX (Fresnel) = 14 dB (96%)
Probe tip (glass side) to ORX = 2 dB (36.9%)
PIN = -19 dBm (12.6 uw) sensitivity, 0 dBm overload
APD = -25 dBm (3.2 uw) sensitivity , <u>-7 dBm overload</u>
ORX roll-off for AC coupling = 35 KHz → 3mm/s

Example with 500 mw laser into circulator
BR probe emits 377 mw to air (20.6+4=24.6% loss)
Laser BR at probe (→ ORX) = 20 mw (4%), +13 dBm
Set VOA, ORX overload = 11 dB (PIN), 18 dB (APD)
Min. target reflection, PIN ORX = -6 dBm (251 uw)
Min. target reflection, APD ORX = -5 dBm (316 uw)
Min. probe efficiency = 0.05% (PIN), 0.06% (APD)

Typical system <u>losses</u> (1550 nm, VOA=0)
Laser to probe tip (glass side) = 1.2 dB (24.1%)
Laser to ORX (via coupler tap) = 23 dB (99.5%)
Probe tip (glass side) to ORX = 4.5 dB (64.5%)
PIN = -19 dBm (12.6 uw) sensitivity, 0 dBm overload
APD = -25 dBm (3.2 uw) sensitivity , <u>-7 dBm overload</u>
ORX roll-off for AC coupling = 35 KHz → 3mm/s

Example with 500 mw laser into tap coupler
NBR probe emits 380 mw to air (24.1% loss)
Laser to ORX (tap coupler) = 2.5 mw (0.5%) = +4 dBm
Set VOA, ORX overload = 4 dB (PIN), 11 dB (APD)
Min. target reflection, PIN ORX = -10.5 dBm (89 uw)
Min. target reflection, APD ORX = -9.5 dBm (112 uw)
Min. probe efficiency = 0.018% (PIN), 0.022% (APD)

Example PDV Equipment Costs

Fiber ring laser source (2 watt) > $20K
High speed real time oscilloscope (10 gig) > $100K
Post-processing software/computer > $3K plus S/W NRE plus S/W per copy cost
BR probe cost < $100, NBR probe cost >$100 to $thousands
Other costs = packaging, cabling, trigger source

PDV Receiver ModBlock Types

Model Number	Receiver Type	RF Output Coupling	Probe Type	Spotting Laser?	Price Each
F170A-AC	PIN-TIA	AC	Back-Reflecting	No	$12,225
F170A-DC	PIN-TIA	DC	Back-Reflecting	No	$13,100
F171A-AC	APD-TIA	AC	Back-Reflecting	No	$13,675
F171A-DC	APD-TIA	DC	Back-Reflecting	No	$21,950
F172A-AC	PIN-TIA	AC	Non-Back-Reflecting	No	$12,675
F172A-DC	PIN-TIA	DC	Non-Back-Reflecting	No	$13,550
F173A-AC	APD-TIA	AC	Non-Back-Reflecting	No	$14,100
F173A-DC	APD-TIA	DC	Non-Back-Reflecting	No	$22,400
F175A-AC	PIN-TIA	AC	Back-Reflecting	Yes	$13,875
F175A-DC	PIN-TIA	DC	Back-Reflecting	Yes	$14,750
F176A-AC	APD-TIA	AC	Back-Reflecting	Yes	$15,325
F176A-DC	APD-TIA	DC	Back-Reflecting	Yes	$23,625
F177A-AC	PIN-TIA	AC	Non-Back-Reflecting	Yes	$14,325
F177A-DC	PIN-TIA	DC	Non-Back-Reflecting	Yes	$15,200
F178A-AC	APD-TIA	AC	Non-Back-Reflecting	Yes	$15,750
F178A-DC	APD-TIA	DC	Non-Back-Reflecting	Yes	$24,050

Standard delivery is 6 weeks. Pacing item is the receiver.

PDV Transceiver ModBlock Types

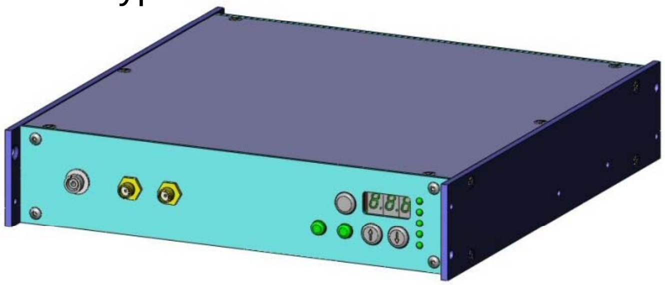
Model Number	Receiver Type	RF Output Coupling	Probe Type	Spotting Laser?	Price Each
F235A	PIN-TIA	AC	Back-Reflecting	Yes	$19,475
F236A	PIN-TIA	DC	Back-Reflecting	Yes	$20,350
F237A	PIN-TIA	AC	Non-Back-Reflecting	Yes	$19,900
F238A	PIN-TIA	DC	Non-Back-Reflecting	Yes	$20,775

Standard delivery is 6 weeks. Pacing items are the laser and receiver.

With 20 mw 1550 nm laser, 40 m min. coherence length

Typical 1/4 rack receiver

Typical 1/2 rack transceiver

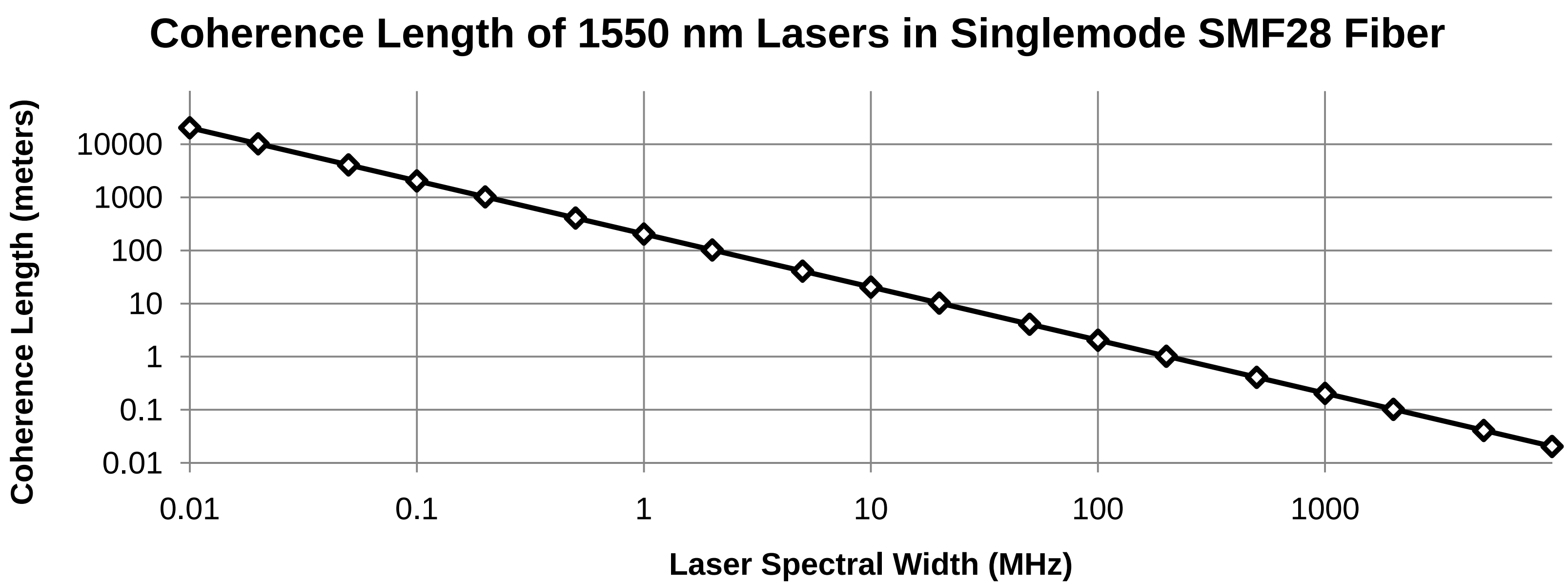


Spotting Laser for PDV Systems

- Visible laser and low loss optical switch added between circulator and probe
- Provides visual diagnostic of probe light alignment to target before executing experimental run
- Adds moderate equipment cost and insertion loss
- Avoids improper experimental run setups

Lasers and Coherence

- CW laser spectral bandwidth (BW) related to coherence length (L)
  - L=c/(n*BW), c=speed of light, n=refractive index of fiber=1.4682 @ 1550 nm
- 1-20 mw 1550 nm communication lasers BW = 1 to 5 MHz typical
  - Low cost, low power, for 200-40 meter roundtrip PDV systems
  - Low cost tunable versions available in C-band
- 2 watt 1550 nm fiber ring lasers BW < 100 KHz typical
  - High cost, high power, for 2 km round trip PDV systems



Optically Amplified Laser Sources

- Few commercial CW laser choices between 20 mw and 2 watts
  - Circulators rated 500 mw maximum
- Optical amplifier can be used to boost coherent laser power
  - Low cost communication laser can be used
  - Optical amplifier maintains coherency
  - Single wavelength optical amplifiers used
  - Output power outputs in the 100 mw (low cost) to 1 watt range

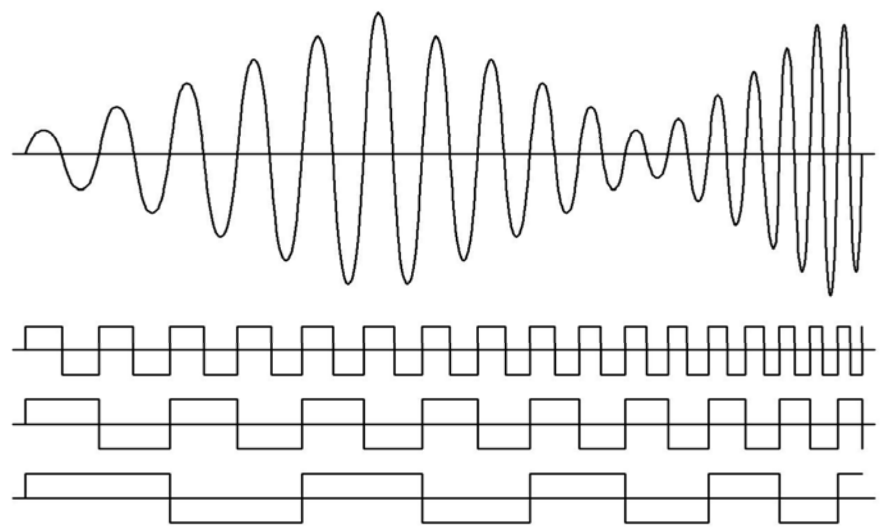
Interferometry approximation for PDV

- Interferometer is fundamentally position based
  - Reinforcement or cancellation interference occurs in wavelength increments (1.55 um)
- PDV interferometer used to measure velocity, not position
  - 1.29 GHz per km/sec is rate of reinforcements <u>and</u> cancellations at receiver output
  - 645 MHz per km/sec is rate of reinforcements <u>or</u> cancellations at receiver output
  - Velocity information is provided by frequency, not amplitude
  - Position resolution several orders of magnitude better than what is needed for velocity
- Final velocity profiles from post-processing software are inherently grainy
  - Velocity profiles typically plotted on a linear scale with no better than 0.1% resolution
  - 0.1% resolution of 10 km/s full scale is 10 m/s resolution
  - 10 m/s is a 6.45 MHz rate of reinforcements <u>or</u> cancellations
- This means that the receiver output rate could be divided down
  - No perceptible resolution loss on the final velocity profile
  - Real time oscilloscope bandwidth could be reduced
  - Special fast counter circuit can be used to directly generate velocity profile
- Nice research and simulation science project for someone
  - Show divider modulus versus velocity profile resolution loss and target maximum speed

Limiting Amplifiers and Frequency Dividers

- Special microwave amplifiers can remove amplitude variations from receiver output over a wide range (1000:1)
  - Eases post-processing software tasks
- Microwave divider can range amplifier output to lower frequencies
  - Negligible loss in velocity profile resolution
  - Lower oscilloscope BW and cost
  - Can provide oscilloscope trigger

Example analog
(variable frequency and amplitude)
and digital waveforms -
receiver output,
amp output,
divide by 2 and 4 outputs



Counter with DAC and/or RAM

- High speed circuitry with a special high speed counter, DAC output (for analog velocity profile) and/or RAM (for digital velocity profile)
  - Can replace real time oscilloscope and post-processing software
  - Can directly provide velocity profile outputs
- Microwave amplifier and divider can range into relatively low cost semiconductors
  - Divider not required for low velocity applications
  - Very high speed counter circuitry possible at higher cost to reduce divider modulus
- Counter output stored in RAM, then RAM and/or DAC read out
- Result scaled by divisor to recover original velocity profile

Single Box PDV Systems

- A variety of single box PDV systems become possible
- All PDV items contained in one enclosure, except probe
- Can be customized to the application
- For 20 mw to 500 mw range
- Coherence lengths up to 200 meters, 40 meters best
- Direct velocity profile outputs, analog and/or digital
- Extendable to many channels
- Significantly lower cost than classical PDV systems

Food for Thought

What could be measured with these commonly available telecom devices?

Temperature or chemical composition changes?

Better triggers? Channel tags? Multiple channels? Target direction?

- Optical modulators - DC to >10 GHz telecom optical amplitude and phase modulators
- Tunable lasers and filters
  - C-band telecom tunable lasers and filters
  - Fast tunable lasers (optical coherence tomography?)
  - Femto-second pulse lasers
- Fast tracking, wide range clock recovery circuits (aka phase locked loops)
  - Could be used instead of counter/DAC/RAM method for direct velocity profile readout
  - “Cook-off” oscilloscope triggers to reduce false triggering
- Optical time delays - Time multiplex multiple PDV channels to one oscilloscope
- Other - Electronic variable optical attenuators, fast optical switches (ns to ps ranges), WDM splitters and combiners with many laser colors, wavelength converters, FC/UPC connectors instead of FC/APC, fast optical scanners

Conclusion

- PDV systems for NBR perform better than BR systems (factor of 2.7)
- Use AC coupled PIN receivers where possible, lowest cost, best availability
- Little technical advantage to using APD receivers, higher risk of overload damage
- Spotting laser is useful add-on to PDV system for diagnostics
- Optically amplified communication lasers can fill 20 mw to 1 watt availability gap
- Coherence length requirements below 200 meters allow lost cost laser use
- Interferometry resolution overkill for PDV velocity measurements
- Special amplifiers after receiver can make post-processing easier
- Frequency dividers after receiver can reduce oscilloscope requirements and costs
- High speed counter circuitry with DAC and/or RAM
  - Can replace real time oscilloscopes and post-processing software
  - Can provide direct analog and/or digital velocity profile outputs
- Many other telecom devices might be usable for PDV material science research

Third Millennium Engineering

Helping customers create and manufacture advanced technology products for our future

Can supply any PDV system or equipment required or shown in this paper

- Supplier of high quality custom engineered equipment, products, and systems using fiber optic, microwave, RF, or advanced technologies
- Quantities from 1 to 10+ units in typically 2-3 months
- Simple to complex, typically multi-functional, provided with any features and accessories needed
- Formal specifications not required, verbal specifications and goals adequate to produce quote
- Consulting, Engineering, Manufacturing, Support
- Commercial, Industrial, Defense, Emerging Industries

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